

# NAVIGATION PERFORMANCE OF THE 2018 INSIGHT MARS LANDER MISSION

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The NASA InSight spacecraft was launched successfully from Vandenberg Air Force Base on an Atlas V 401 launch vehicle on May 5, 2018 and landed on November 26, 2018. Accurate targeting to the atmospheric entry point by the Navigation team achieved by carefully controlling the final entry flight path angle to -12.0 degrees with a tolerance of  $\pm 0.21$  degrees. This paper will describe how the InSight Navigation team met this difficult task in the presence of frequent unbalanced thrusting for attitude control. The continuous correction for this unplanned  $\Delta V$  far exceeded pre-launch expectations and proved a challenge to predict accurately.

## INTRODUCTION

The Interior Exploration Using Seismic Investigations, Geodesy, and Heat Transport Mission (InSight) is a NASA Discovery Program mission with the objective of using a single geophysical lander on Mars to study its deep interior. InSight already deployed the seismometer on December 18, 2018. The surface penetrator will be deployed in the next several weeks. These two science instruments will investigate the fundamental processes of terrestrial planet formation and evolution.

The InSight Mission is based on the proven Phoenix Mars spacecraft and lander design with state-of-the-art avionics from Juno and the Gravity Recovery and Interior Laboratory (GRAIL) missions. The spacecraft was built by Lockheed Martin and inherited many of its designs and mission concepts from these previous missions. National Centre for Space Studies (CNES) provided

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the Seismic Experiment for Interior Structure (SEIS) and Deutsches Zentrum für Luft- und Raumfahrt (DLR) contributed the Heat-Flow and Physical Properties Probe (HP<sup>3</sup>).

InSight was originally proposed with a launch date in March 2016, but technical problems made this impossible. The InSight spacecraft (including the entry vehicle, cruise stage and lander) launched on the first day of the next Earth-Mars opportunity on May 5, 2018 and successfully landed on Mars on November 26, 2018.

## **Science Objectives**

InSight is not simply a Mars mission; it is a terrestrial planet explorer that will open a window into the processes that shaped the rocky planets of the inner solar system more than four billion years ago. It will also investigate the dynamics of Martian tectonic activity and meteorite impacts, which could offer clues about such phenomena on Earth. The primary science goals are (1) to understand the formation and evolution of terrestrial planets through investigation of the interior structure and processes of Mars, and (2) to determine the present level of tectonic activity and impact flux on Mars. These general goals have been narrowed down to the following specific objectives<sup>1</sup>:

- Determine the thickness and structure of the crust
- Determine the composition and structure of the mantle
- Determine the size, composition, and physical state of the core
- Determine the thermal state of the interior
- Measure the rate and geographic distribution of seismic activity
- Measure the rate of meteorite impacts on the surface

These objectives will be accomplished through the use of the SEIS instrument, a high-precision, broad-band seismometer that monitors seismic activity and tidal displacements; HP<sup>3</sup> which will determine the geothermal heat flux by penetrating below the surface to a depth of at least 3 m; and RISE, a landed X-band Doppler experiment to track and improve estimates of the planet's rotation.

## **MISSION**

Generally speaking, the principal mission phases are:

*Launch:* The Launch phase begins when the spacecraft transfers to internal power prior to launch and ends when the Flight System achieves a thermally stable, positive energy balance, with the radio link established.

*Cruise:* The Cruise phase, which encompasses the majority of the interplanetary transfer to Mars, begins when the Launch phase ends and ends three hours prior to Mars entry interface when the final EDL parameter updates are activated in the onboard sequence.

*Entry, Descent, and Landing (EDL):* The Entry, Descent, and Landing phase begins three hours prior to the Mars atmospheric Entry Interface Point (Mars radius equal to 3522.2 km) and ends with confirmation on the Earth that both landed solar arrays are deployed, positive thermal/power balance state is achieved, a functioning radio link exists, uplink loss timer is reset, and surface fault protection is enabled.

*Surface Operations:* The Surface phase begins when the EDL phase ends and ends when the primary mission is complete (nominally 1 Mars year plus 41 sols from landing). Since the project needs for Navigation have already been met at this stage, there will be no discussion of the Surface Operations Phase in this document.

## SPACECRAFT

The InSight spacecraft hardware design was based on the 2007 Mars Phoenix Lander Mission, with component updates and modifications as necessary. The spacecraft is composed of 3 major components: The InSight lander with the scientific instruments, the aeroshell, and the cruise stage. The lander contains all of the spacecraft avionics, the propulsion subsystem, the surface power components, the surface telecom components, and the surface payload. The aeroshell (backshell and the heatshield) protects the lander during until it is discarded during entry. The cruise stage separates from the aeroshell before entry and contains the cruise power and telecom components. The cruise propellant and EDL propellant share a common propulsion system.

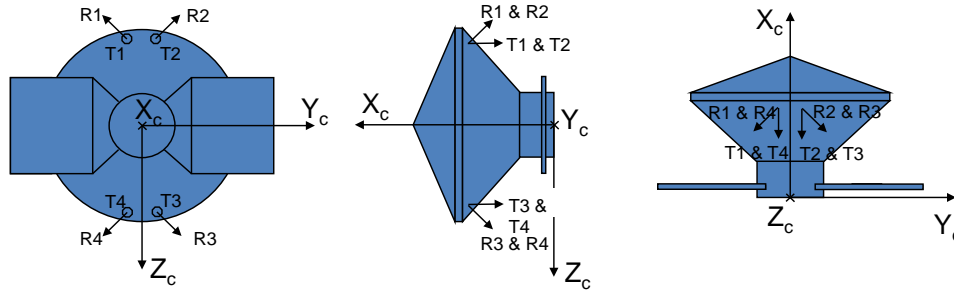
The solar array normal points in the direction of the spacecraft X axis. The low gain antenna (LGA) is attached to the cruise stage and oriented in the same direction. The boresight of the medium gain antenna (MGA) is canted off the X axis towards the +Z axis to provide optimum EDL coverage.

The Attitude Control System (ACS) is the primary system of interest to this discussion. It consists of the star trackers, Sun sensor, and two Miniature Inertial Measurement Units (MIMU). The primary attitude determination is done via the star trackers and MIMU system. The spacecraft is three-axis stabilized via an unbalanced thruster control system.<sup>2</sup>

The four 4.5N Reaction Control System (RCS) thrusters were fired intermittently to maintain a pre-determined deadband attitude profile defined by spacecraft telecom, power and thermal subsystems. The inner cruise attitude maintained the solar arrays at a 50-degree angle to the Sun, keeping them in the Earth-Sun plane. In late cruise the solar arrays were pointed 2 degrees off Sun. This change was made on July 12, 2018.

The ACS system commanded the thrusters to fire each time the attitude reached one side of the deadband. The tighter the deadbands, the more thrusting was needed to keep the attitude inside the constraints, which imparted more  $\Delta V$  and more uncertainty into the trajectory. The deadbands in early cruise were  $[10^\circ, 10^\circ, 7.5^\circ]$  in the spacecraft system, and reduced to  $[4^\circ, 4^\circ, 4^\circ]$  for late cruise. Each RCS thruster has a component of thrust in all three spacecraft body axes. Thrust in the Y and Z directions are designed to be balanced, but not in the X direction. As a result, each time an RCS thruster is fired there is a  $\Delta V$  imparted along the spacecraft +X axis direction. The accumulation of these +X  $\Delta V$ s and the unbalanced components in Y and Z caused a continuous perturbation to the trajectory, one that was not easily modeled. Past small forces were queried daily from spacecraft telemetry.

The same RCS system was used for the slews needed for spacecraft velocity changes ( $\Delta V$ ). Every propulsive maneuver was decomposed into different segments for the slews, main burn, and other smaller effects (pointing corrections, etc.) with the total meeting the desired  $\Delta V$ . This was accurately performed by the Lockheed Martin GNC team. However, the discrepancies between modelled and actual thruster directions invariably introduced errors in the implemented  $\Delta V$ . For later small maneuvers this effect dominated the orbit determination errors. Hence the estimation and prediction of these thruster pulses, or small forces as they are commonly referred to, was one of the primary tasks for InSight Navigation during cruise.



**Figure 1. InSight Thruster Configuration**

## NAVIGATION DESIGN

The driving requirement for Navigation was to accurately deliver the vehicle to the Entry Interface Point (EIP) at the top of the atmosphere defined at a Mars radius of 3,522.2 km. The desired entry flight path angle was -12.0 degrees, and Navigation was required to meet this within 0.21 degrees ( $3\text{-}\sigma$ ). The targeted entry flight path angle could be changed by up to 0.15 degrees in either direction by the EDL Team in case of large atmospheric changes.

This requirement was derived from landing site safety concerns. The “E9” landing site was selected before launch as the best option. This was based on analysis of detailed imagery from the MRO HiRISE camera to classify threats to a safe landing and instrument deployment. The E9 landing site at 4.51 degrees north latitude and 135.99 degrees east planetocentric longitude was based upon an expected 150 km by 27 km landing 99% ellipse with a landing azimuth of 93 degrees<sup>3</sup>.

The size of the landing ellipse was determined by errors in Navigation delivery and errors in EDL performance. The ground ellipse is often described with along-track errors (ellipse major axis) and cross-track errors (minor axis). The Navigation delivery errors have little effect in the cross-track direction and so the entry flight path angle (EFPA) was selected as the single variable to control. Large errors in EFPA (up to one degree) then have the effect of delivering the spacecraft too far uptrack or downtrack to meet landing site safety requirements. At the extremes, a very shallow entry might not provide sufficient drag for landing (a “skip out”), and very steep entry carries the risk of vehicle overheating. The selection of -12.0 degrees EFPA balanced these risks and allowed a Navigation delivery error of 0.21 degrees ( $3\text{-}\sigma$ ).

An additional requirement was that the entry time should change by less than 30 seconds in order to support EDL communications with the Mars Reconnaissance Orbiter spacecraft (MRO). MRO recordings of EDL data were necessary to support analysis of EDL after the fact, especially if any failure occurred. MRO had changed its orbit to support InSight EDL in order to be at the correct location and orientation during EDL, and link margin was very sensitive to changes in entry time (especially given that the orbits of InSight and MRO were essentially perpendicular).

## Orbit Determination

Orbit determination uses radiometric data to estimate the position and velocity of the spacecraft at a moment in time, to solve for or reconstruct spacecraft events in the past, and also to predict its state at a future time. This requires very precise and accurate dynamic models.

The three data types used in the cruise phase were two-way Doppler, two-way Ranging and Delta Differential One-way Range (DDOR). The two-way Doppler measurement uses the Doppler effect of a signal from a DSN antenna to the spacecraft and back to measure the line-of-sight velocity of spacecraft. Two-way Ranging uses the same signal to measure the distance between a

DSN antenna and the spacecraft. DDOR is used to measure the position of the spacecraft in the geocentric plane-of-sky. Each of the data types were processed using an X-band signal transmitted to the spacecraft and an X-band signal transmitted by the spacecraft in return. The Doppler and range measurements were collected according to the general schedule in Table 1, and the DDOR schedule is shown in Table 2. Additional 34-m tracking was added around trajectory corrections and the thruster calibration but have been removed for brevity.

**Table 1. Baseline Doppler and Range Tracking Schedule**

Relative Dates	Support
Launch to L + 30 days	Continuous 34-m coverage
L + 30 days to E - 141 days	One 34-m 8-hour pass/day
E - 140 days to E - 124 days	Two 34-m 8-hour passes/day
E - 123 days to E - 65 days	Five 34-m 8-hour passes/week
E - 64 days to E - 31 days	Two 34-m 8-hour passes/day
E - 30 days to E - 15 days	Continuous 34-m coverage
E - 15 days to E - 5 days	Continuous 70-m or 34-m redundant
E - 5 days to Entry	Continuous 70-m or 34-m redundant + two 4-hour 35-m

The use of DDOR measurements was critical for Navigation success. Without DDOR data the InSight mission would not have been able to meet the entry delivery requirements. DDOR measurements were only possible using Goldstone/Canberra and Goldstone/Madrid combinations. The most critical time period for DDOR measurements was on approach to Mars (60 days before entry) but measurements were taken regularly before this time for analysis and evaluation. However in early October the frequency was increased to nearly once per day from each pair.

**Table 2. Baseline DDOR Tracking Schedule**

Start Date	End Date	Stations	Sessions
June 14, 2018	Oct 12	GLD/CAN	21
(E-165d)		GLD/MAD	0
Oct 13	Nov 11	GLD/CAN	20
(E-44d)		GLD/MAD	16
Nov 12	Nov 18	GLD/CAN	7
(E-14d)		GLD/MAD	7
Nov 19	Nov 25	GLD/CAN	8
(E-7d)		GLD/MAD	8
TOTAL		All	87

The accuracy and consistency of the dynamic models was checked throughout cruise. Pre-launch estimates of solar radiation pressure, thruster direction, etc. are rarely accurate enough in-flight and so these parameters are included in the OD filtering.

The Thruster Calibration on June 26, 2018 was a critical Navigation activity. This was designed to characterize the performance of the individual thrusters by slewing to predetermined attitudes and firing the individual thrusters in sequence. Very briefly, two-way Doppler tracking data during the calibration was combined with 5 Hz spacecraft quaternions and angular velocity telemetry, and a limited amount of 50 Hz angular velocity data from the MIMU. An unscented Kalman filter was used to refine the thrust levels and pointing for each thruster<sup>4</sup>.

### **Flight Path Control**

While the orbit determination task is concerned with finding the spacecraft, the flight path control task is to deliver it accurately to the desired location (as determined by the trajectory analyst). A series of six trajectory correction maneuvers (TCMs) were planned during the Cruise phase of the InSight mission. The primary objectives of the first three TCMs are to remove launch vehicle injection errors and the planetary protection targeting bias. Some small biasing of the aimpoint is necessary before TCM-3 to meet non-nominal impact requirements. The final three TCMs were used for precise targeting of the atmospheric entry conditions and the Mars landing site. Both TCM-5 at E-8 days and TCM-6 at E-22 hours had scheduled backup maneuvers: TCM-5X and TCM-6X. These backup maneuvers would have been executed only if either TCM-5 or TCM-6 were not performed. In addition, TCM-6XM would be selected from a pre-determined menu of candidate maneuvers designed to minimize the target miss on the Mars surface. This option could be used if a major execution error occurred at TCM-6. TCM-6X and TCM-6XM shared the same execution time.

All InSight TCM designs were subject to execution errors. For TCMs under 5 m/s in magnitude, the requirement on these execution errors was approximately 9 mm/sec ( $1-\sigma$ ) in the direction of the burn and 14 mm/sec ( $1-\sigma$ ) in side velocity error. This was a significant factor in the choice of later TCMs, as these propagated errors began to dominate the orbit determination errors.

Table 3 lists these maneuvers, their location, date, and purpose. The locations of the TCMs were chosen as a compromise between competing factors:

- Provide sufficient time between Launch and TCM-1 for spacecraft checkout and design of TCM-1
- Provide sufficient time between TCMs to allow for TCM reconstruction, orbit determination, and sequence generation for the upcoming TCM
- Minimize operational complexity by following heritage timelines
- Minimize Mars atmospheric entry delivery errors

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**Table 3. Maneuver Schedule**

Event	Location	Date (UTC, 2018)	Executed?	Objective
TCM-1	L + 17d	May 22	Yes	Remove most of injection errors
TCM-2	E - 121d	July 28	Yes	Correct for TCM-1 and orbit determination errors
TCM-3	E - 45d	Oct. 12	Yes	Correct for TCM-2 and orbit determination errors All subsequent TCMs target to desired landing site
TCM-4	E - 15d	Nov. 1	Yes	Correct for orbit determination and TCM-3 execution errors
TCM-5	E - 8d	Nov. 18	No	Correct for orbit determination and TCM-4 execution errors
TCM-5X	E - 5d	Nov. 21	No	Contingency - Same objectives as TCM-5.
TCM-6	E - 22h	Nov. 25 21:40	Yes	Final targeting to landing site.
TCM-6X	E - 8h	Nov. 26 11:40	No	Contingency - Final opportunity for entry targeting maneuver.
TCM-6XM	E - 8h	Same	No	Contingency - Final opportunity for entry targeting maneuver. Selected from pre-determined menu of validated maneuvers to maximize the probability of successful landing.

The design of the predetermined “menu options” for TCM-6XM was based on a scenario in which TCM-6 had either failed to execute outright, or had some anomalously large error. Because they were designed and tested already on the ground the response time to errors of this sort was minimized. To fit this scenario they needed to cover the possible TCM-5 delivery, and hence were not suitable for last-minute tweaks after a nominal TCM-6. The InSight flight path control analysts developed an algorithm to generate these maneuvers in the local velocity frame of the spacecraft rather than matching dispersed points on the ground (as had been done for the Phoenix Mission)<sup>5</sup>. This algorithm reduced the number of  $\Delta V$  magnitudes and directions required and simplified the implementation and testing of these “canned” maneuvers.

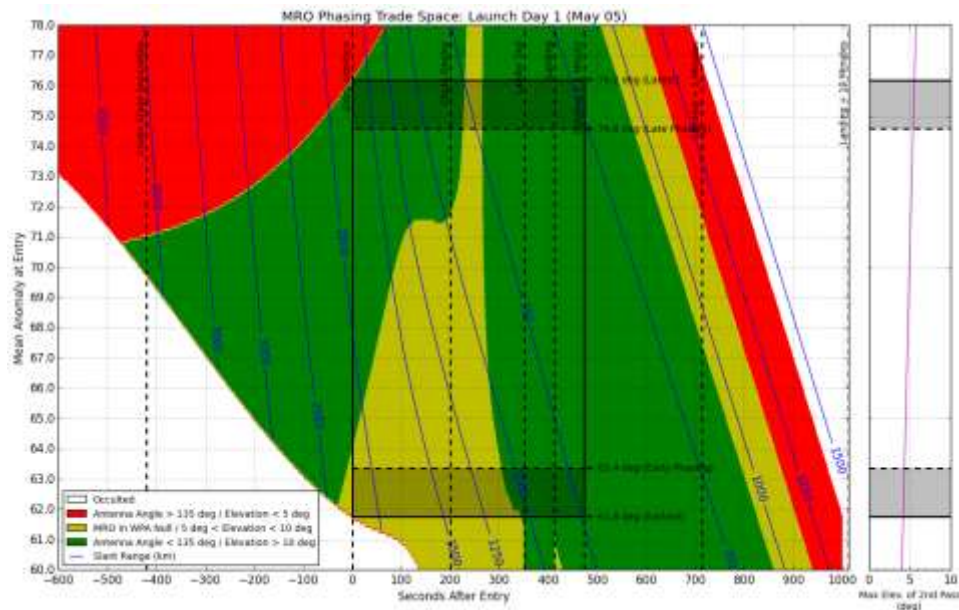
### Trajectory Analysis

The trajectory analyst has many tasks pre-launch, including the launch/arrival analysis which satisfies many mission design requirements and constraints. Primary among these is the targeting to preserve the EDL communications link. This carried over into cruise operations. Small but significant tweaks to the desired trajectory were necessary to preserve the direct-to-Earth (DTE) UHF links and to coordinate with the MRO Navigation team<sup>6</sup>. Regular generation and distribution of ideal or “reference” cruise trajectories kept the Navigation Team and other project teams working to the same baseline.

InSight Navigation was responsible for providing a phasing target for MRO through the EDL Relay Targets File (ERTF). The coverage requirement covered Entry through landing plus one



minute. As shown in Figure 2 this accounted for the MRO antenna pattern and the MRO elevation above the landing site. The fact that InSight approached from the west and MRO's inclination is near 93 degrees meant that a very brief time period was available for EDL communications. The dark horizontal bands in Figure 2 indicate the anticipated MRO timing prediction accuracy of 30 seconds.



**Figure 2. InSight / MRO Phasing Trade Space**

Direct to Earth coverage of EDL was also planned for radio telescopes at Green Bank, WV and Effelsberg, Germany using a UHF link. It was determined before launch that the elevation of these stations above the local Mars horizon was greater than 10 degrees throughout the EDL communications period for most launch dates, and above 9.7 degrees for those exceptions. The trajectory analyst was responsible for providing frequency predictions to Green Bank and Effelsberg during cruise.

### EDL Trajectory Analysis

Orbit determination and flight path control are concerned with the position and velocity of the spacecraft before it enters the atmosphere, and the cruise trajectory analyst with propagations to the ground. The task of modeling the flight during EDL fell to the EDL Trajectory analyst. Their responsibility was to maintain the primary entry simulation tool DSENDS (Dynamics Simulator for Entry, Descent and Surface landing) used for TCM targeting, and to interface with the JPL EDL Team.

During the weeks before EDL the EDL trajectory analyst had an additional duty. An agreement was reached between the Aerothermal/EDL Systems Team and the Landing Site Safety Team that changes to the landing site were permissible if the Mars atmosphere had changed. This also mitigated the need for late trajectory corrections. The tolerance on the ground was 19 km in the uptrack direction (shallower EFPA) and 10 km in the downtrack direction (steeper EFPA). If the resulting landing site with updated atmosphere and wind models lay within this range, when targeted with an EFPA of -12 degrees, then the baseline would be updated to reflect the new models. If not, the target tolerance of 0.15 degrees would be used to move the landing site within the ground tolerance.

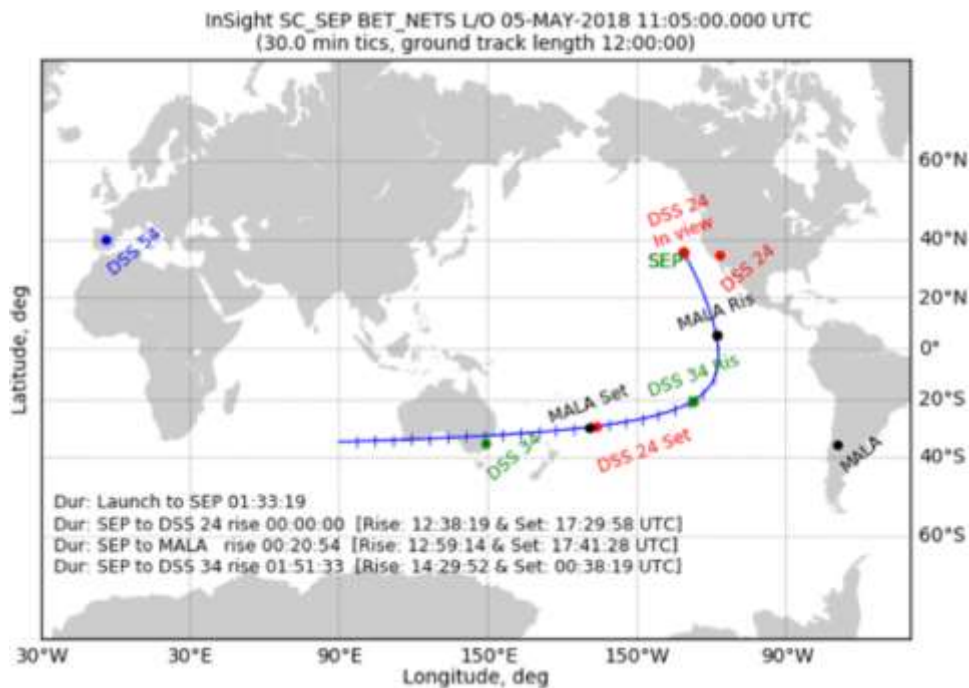
Atmosphere model updates were provided frequently in the last two weeks of cruise, produced by the InSight Council of Atmospheres. Using the ground tolerance negated the need for small TCMs to “chase the atmosphere” and usually amounted to only a few kilometers<sup>7</sup>.

Finally, the EDL Trajectory analyst had the responsibility of calculating landing site safety for particular orbit determination and TCM combinations. This reflected the current Navigation delivery and EDL performance and provided important context for TCM decision-making.

## LAUNCH OPERATIONS

InSight was the first interplanetary mission launched from Vandenberg Air Force Base (VAFB) in California. The launch period of the Atlas V-401 was from May 5 to June 8, 2018, and the launch took place at the first opportunity at 11:05 UTC. The selection of the launch and arrival conditions was primarily determined by the need for communication during EDL, with signals received at radio telescopes on Earth and the Mars Reconnaissance Orbiter (MRO) spacecraft<sup>8</sup>, as well as a number of other considerations such as the hyperbolic excess velocity at arrival ( $V_{\infty}$ ).

It was the responsibility of Navigation to provide pre-launch trajectory predictions to the NASA Deep Space Network (DSN) and the ESA ESTRACK stations and to update these predictions after launch. Trajectory variations due to upper stage errors, etc. can have significant effects within only a few hours, which would require the DSN to begin a predesigned search pattern if the spacecraft is not found within the station beam width. Similarly, investigating the state of the spacecraft post-launch is of great importance to the project and the spacecraft operations team, and this cannot be done without a communications link for telemetry. Hence the initial acquisition of the spacecraft is a time-critical activity.



**Figure 3. InSight Post-Launch Ground Track**

The launch of an interplanetary spacecraft from the west coast presented a unique challenge. An Earth-Mars mission from the Kennedy Space Center in Florida typically is launched in an eastern direction over the Atlantic Ocean, passing near South Africa and Australia before continuing to the

north Pacific. At that point, the separation from the upper stage might be visible from Australia, Japan or California. The Doppler and range navigation data from a long tracking pass would be used to create a valid orbit determination solution, and trajectory predictions generated for the second and subsequent passes.

The situation for InSight was quite different. A western launch from southern California, combined with the necessary coast times and departure asymptote, meant that the spacecraft separation would be visible at the DSN Goldstone complex<sup>9</sup>, relatively close to the launch site itself as shown in Figure 3. The rapid departure from the Earth meant that the second pass would begin less than 2 hours after the first, which is insufficient time for a dependable solution. InSight was then in the unusual predicament of having two “initial acquisition” passes based on pre-launch predicts.

The acquisitions at Goldstone, CA and Canberra, Australia were flawless. One-way tracking data was available from Goldstone within 30 seconds of separation, as designed, indicating a healthy spacecraft in the expected safe mode configuration. The commands to switch to two-way Doppler were sent in a timely manner and this data type was received 42 minutes after separation. Range data was received shortly thereafter (59 minutes post-separation). The first orbit determination solution used a data arc from 13:21 UTC to 15:35 UTC on launch day, and the data cutoff (time of last measurement) for the next was near 19:00 UTC that day. This solution was used to generate predictions for the DSN pass at Madrid later on launch day. Post-launch analysis showed that the Centaur upper stage performed at a 1.22- $\sigma$  error level (31.5% probability), far below the mission accuracy requirement.

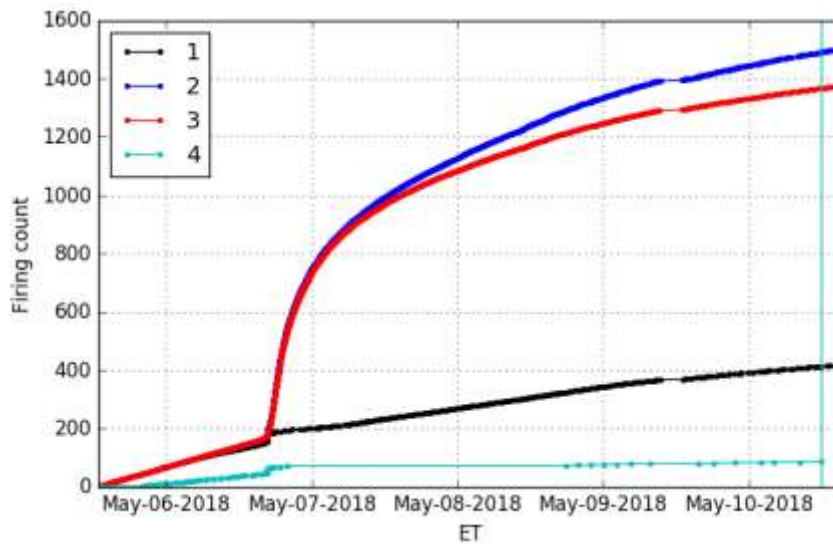
## **CRUISE OPERATIONS**

### **Post-Launch Operations and TCM-1**

The baseline plan post-launch called for execution of TCM-1 at Launch + 10 days. The orbit determination data cutoff would take place 5 days before that, with reasonable amounts of time allocated to each subsequent team for design and testing of TCM products. This timeline has been executed successfully on other missions and there was no reason to expect that InSight would be any different.

These expectations were changed as soon as small forces telemetry was received. This indicated that the attitude controller was commanding very frequently in the first day of cruise -- approximately 5 times more than anticipated. Firing rates increased even further when the spacecraft was commanded to cruise attitude on May 6. The Navigation team quickly developed models to account for these accelerations, but projecting them into the future was difficult because of the lack of understanding of the underlying problem. The project conclusion was that this was a component out-gassing event caused by the 2-year storage of the spacecraft from its original 2016 launch date. The aeroshell may have been the main culprit, given that its composition is somewhat porous. No post-storage bake-out had been performed, and so the accumulated water vapor began to immediately evaporate upon exposure to the sun. This also explained the sudden increase after the attitude change. GNC torque simulations performed at Lockheed Martin were consistent with a thrust in the general area of a backshell vent.

Nevertheless, at Launch + 5 days when a definitive solution was expected, the small force firings were still significant as shown in Figure 4. There were signs that the rate of firing might soon reach a steady state, but future prediction was still challenging because poor knowledge of the actual deadbanding velocity changes.

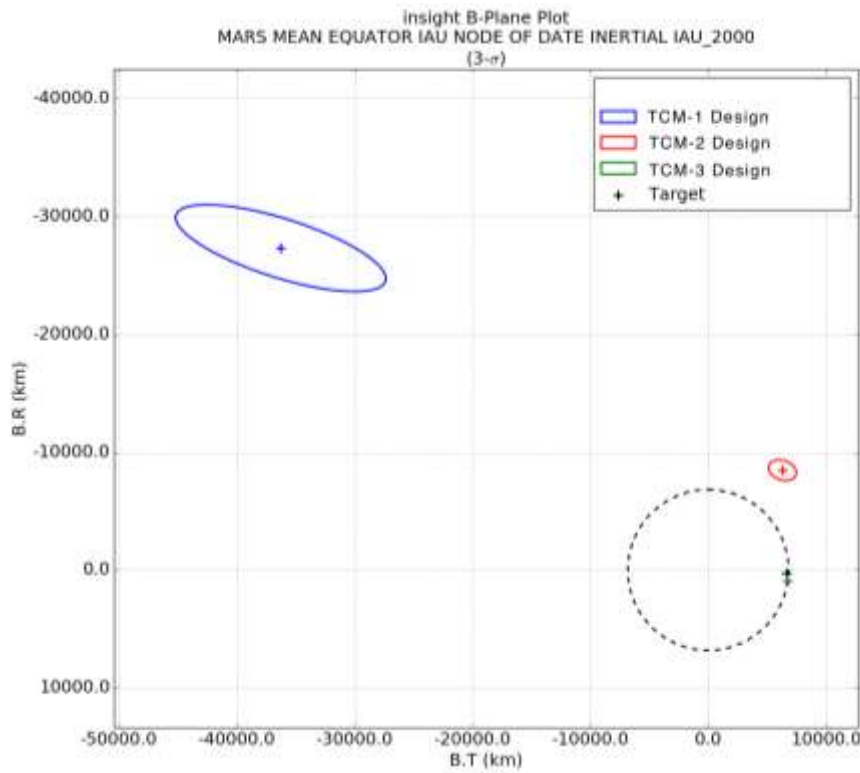


**Figure 4. Pre-TCM-1 Attitude Thruster Firings**

Three decisions were made to reduce the effect of these unknown forces. First, the execution of TCM-1 was delayed by a week, allowing Navigation more time to develop a good predictive model and watch the evolution of the outgassing. Second, the flight path control team opted to use both TCM-1 and TCM-2 to target entry. This delayed some of the correction to TCM-2 when models would be improved. The final TCM-1  $\Delta V$  was 3.78 m/sec when paired with 1.91 m/sec at TCM-2, instead of performing 4.85 m/sec entirely at TCM-1. The additional 0.04 m/sec cost was negligible. Finally, the project implemented a spacecraft bake-out after TCM-1, rotating the spacecraft to two of the thruster calibration attitudes for a few days. Additional outgassing was observed at these attitudes but with less dramatic effect.

### **Thruster Calibration and TCM-2**

After the execution of TCM-1 and the bake-out, Navigation began the process of refining the small forces models and testing them against actual data. The next major event during cruise was the Thruster Calibration on June 26, 2018. As previously mentioned, the analysis of the Thruster Calibration is not the subject of this paper, but is covered extensively in Reference 4. Its effect on the trajectory was significant, however, as the imparted  $\Delta V$  from the slews and thruster firings amounted to 0.492 m/sec. This  $\Delta V$  was included in the TCM-1 / TCM-2 design at the expected level (0.472 m/sec) and TCM-2 served as a cleanup maneuver in addition to targeting to the landing site. An additional activity took place on July 12, 2018, also before TCM-2. At this point the spacecraft turned to an attitude such that the solar panels faced the sun more directly, and the deadband limits were reduced to 4 degrees in each axis. This caused some minor outgassing as seen in the two-way Doppler, and also changed the nature of the deadbanding from one-sided to two-sided, and as such the small force models underwent further refinement. The net  $\Delta V$  of 0.035 m/sec was easily absorbed by the TCM-2  $\Delta V$ . The B-plane miss distance at TCM-2 is shown in Figure 5 which required a magnitude of 1.498 m/sec.



**Figure 5. InSight B-Plane at TCM Design Epochs (Early Cruise)**

### TCM-3, TCM-4 and TCM-5

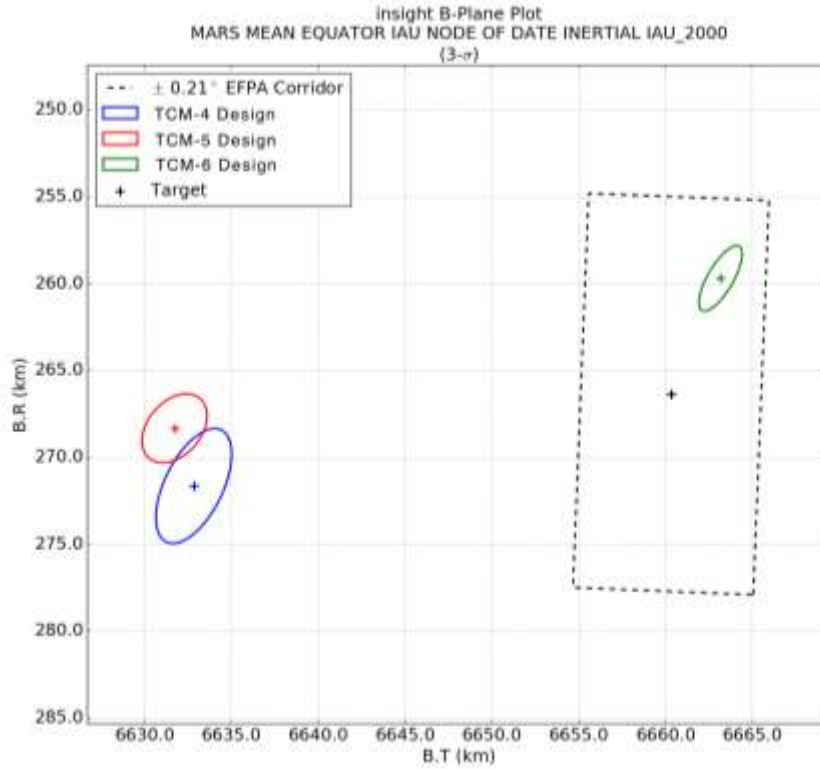
TCM-3 was the first of the approach maneuvers, all of which targeted the landing site directly using DSENDs, rather than using B-plane targeting as a proxy. It was executed at Entry - 45 days (October 12, 2018) and corrected a TCM-2 overburn and any changes to the small forces from the prediction. The B-plane miss is visible in Figure 5 slightly to the south of the entry target. The spacecraft implementation also reflected the final targeting strategy as the duty cycle of the thrusters was reduced to 35% from 80%, allowing a longer burn and more time for the controller to correct startup transients.

Orbit determination solutions had stabilized at this point thanks to the more predictable two-sided deadbanding. Thruster firings were still taking place at the rate of over 100 per day. The only benefit to this was more data to fit through. Future small force levels were extrapolated from the past data and had proven to be very accurate, to the extent that the Thruster Calibration results were less critical. The estimates of thrust level and direction were still useful, however.

The desired magnitude of TCM-3 was 0.167 m/sec, much less than the Thruster Calibration, and at this point the option of postponing the correction until TCM-4 came into play. But there was no benefit to a 30-day execution delay and so TCM-3 was executed as designed.

As for TCM-4, the prevalent opinion had been that it would likely be cancelled. This was the case for the Phoenix mission<sup>10</sup> and the same turned out to be true for InSight. This was due to a combination of factors. First, the optimum TCM-4 magnitude was 0.03 m/sec. For very small maneuvers such as this the errors in the slews to and from the burn attitude began to dominate the effect of the maneuver itself, and hence the minimum useful  $\Delta V$  had been set at 0.04 m/sec. It was possible to increase this magnitude by making a 10-second change to the entry time but this would

have interfered with the EDL communication strategy and hence was an imperfect solution. The effect of the slew errors turned out to be the deciding factor. The post TCM-4 1- $\sigma$  delivery ellipse was 17.6 km by 16.4 km, but with a B-plane miss distance of 28 km the 3- $\sigma$  post-TCM delivery enclosed the OD solution (see Figure 6). In other words, the probability of making the situation worse was unacceptably high. Figure 6 also shows a targeting box of  $\pm 0.21$  degrees in the horizontal direction (the requirement) and approximately  $\pm 17$  km in the vertical direction (somewhat arbitrary).



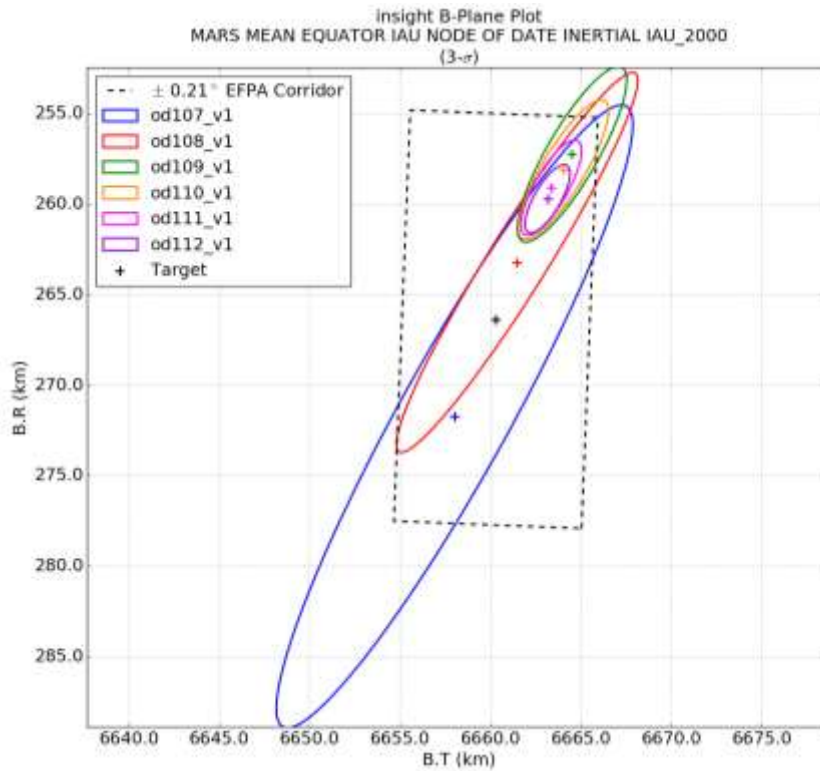
**Figure 6. InSight B-Plane at TCM Design Epochs (Approach)**

There was an increase in the TCM-5  $\Delta V$  magnitude to 0.057 m/sec, but this worked in our favor to exceed the minimum  $\Delta V$ . Fortunately the slew errors at TCM-5 would be at the same level as TCM-4 with less time to propagate, giving a 1- $\sigma$  ellipse of 9.4 km by 6.7 km, and making TCM-5 a viable option. So TCM-4 was cancelled, and TCM-5 was performed instead at its nominal time of Entry - 8 days (November 18, 2018).

### TCM-6

After TCM-5 daily orbit determination solutions were produced, and these are summarized in Figure 7. Solution 'od107\_v1' was the first made after TCM-5 execution and clearly has a significant delivery ellipse, though not unexpectedly large. The gradual motion of the daily solution from the “southwest” of the B-plane target box to the “northeast” and back to the center caused some consternation within the project but simply reflects the time required to reconstruct a maneuver -- and understandable anxiety about events very close to landing. All these solutions are statistically consistent, however, and changes such as this should be expected.





**Figure 7. Pre TCM-6 Orbit Determination Solutions**

Recall that the TCM-6 execution time was 22 hours before Entry. The last tracking data would be taken 24 hours before that, and all necessary implementation and testing steps took place within that 24-hour period. This had been done at TCM-5 for the first time. Significant milestones in the timeline were:

- TCM-6 Design delivery at Entry - 45 hours
- The Landing Site Criteria Evaluation Meeting at Entry - 39 hours
- TCM-6 Go/No-Go Meeting at Entry - 28 hours
- TCM-6 Execution at Entry - 22 hours

TCM-6 was designed with 'od112\_v1' and the 'OPS\_E7BG' atmosphere model to a landing site at 4.500 degrees north, 135.951 degrees east (about 2.4 km west of the E9 landing site). The  $\Delta V$  magnitude was 0.085 m/sec, clearly above the minimum threshold. But even without a burn the EPFA was -11.90 degrees, within the Navigation requirement, and the ground landing site was within the landing ellipse. However as EDL analysis proceeded it became clear that the no-burn landing site was very close to the limit of landing site safety.

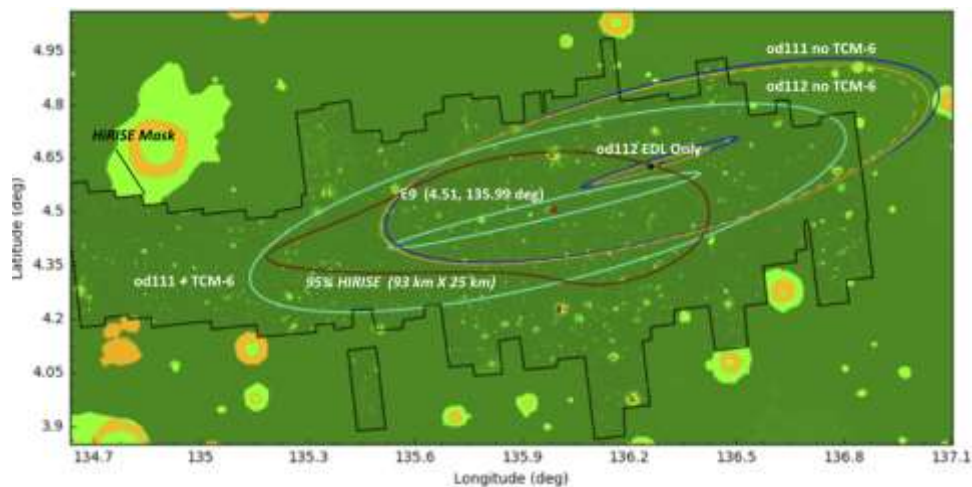
Table 4 was presented at the TCM-6 Go/No-Go Meeting, the final possible decision point. Over the previous hours the landing site safety criteria had hovered around the threshold of action vs. no action. Figure 8 shows the 'od111\_v1' and 'od112\_v1' solutions propagated to the ground as well as the contour at which 95% of the delivery ellipse would be covered by existing HiRISE imagery. The criteria were not satisfied to the letter at the Landing Site Criteria Evaluation Meeting (row marked as "No-Burn od113"), but it was noted that the assessment criteria were not hard limits, and despite the potential for poor terrain in the east part of the ellipse, that they were satisfied to within a reasonable margin of error. Additional solutions and analyses were performed overnight

before the Go/No-Go meeting, and ‘od115\_v1’ showed an improved result from a very small change.

In this case however, the conventional wisdom that TCM-6 would not be necessary was not borne out. At the final decision meeting, most subsystems recommended executing TCM-6 despite its meeting the safety criteria and the project supported this recommendation.

**Table 4. Landing Site Assessment Criteria**

Case	Ground Ellipse	Probability of Terrain Safety	% in HiRISE Zones	% in CTX Zones	Ellipse Center to E9
<i>Assessment Criteria</i>		> 98%	> 95%	< 5%	N/A
No-Burn od113	92.3 km x 25 km	98.9%	94.6%	5.3 %	18 km
No-Burn od115	91.9 km x 25 km	98.9%	95.3%	4.6 %	17 km
TCM-6 od115	100.6 km x 25 km	98.99%	99.7%	0.3%	1.5 km



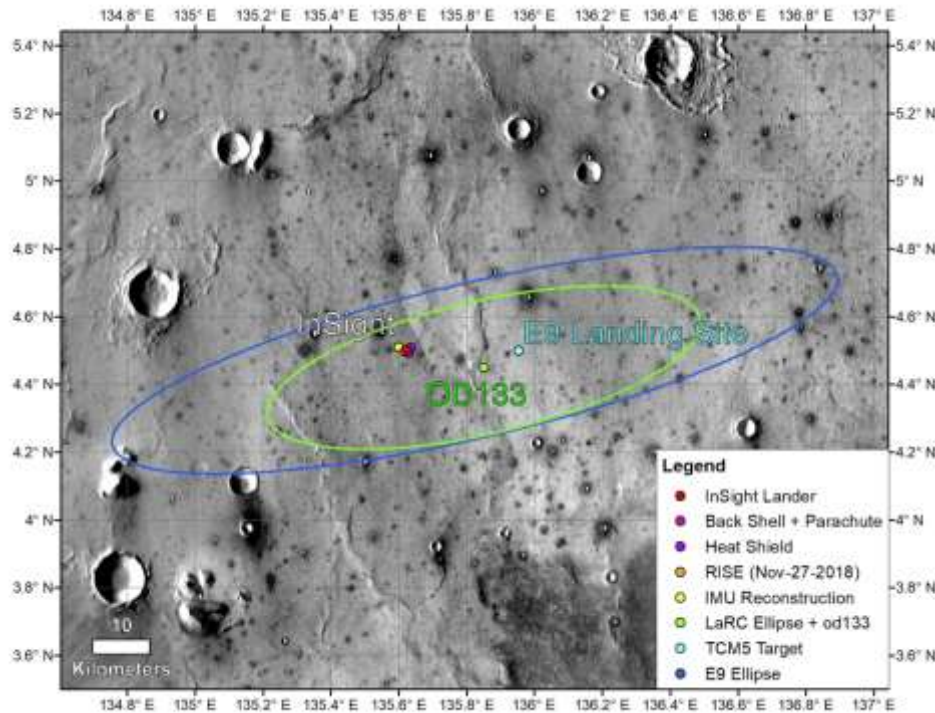
**Figure 8. Final Landing Site Assessment Results**

### Entry, Descent and Landing

After the TCM-6 maneuver had executed, the final tasks were to reconstruct TCM-6 and to monitor the spacecraft on approach to Entry. Recall that a menu of predesigned and pretested TCM-6XM options was available in case of severe problems with TCM-6 if landing site safety required it. Real-time telemetry indicated that the turns and thruster firings had gone as planned but experience had shown that this was not a good indicator of TCM performance. Due to timeline constraints in the AEDL Procedure the data cutoff for Navigation evaluation was only two hours after the TCM and no additional DDOR measurements were possible. This did not provide sufficient information for reconstruction, and so TCM-6XM was called off. This was a situation where a heritage approach did not serve, and these conflicts should have been worked in advance.



Orbit determination analysts produced hourly solutions after TCM-6. The EDL team used these solutions to evaluate the need for updates to the entry parameters (such as entry time, parachute deploy triggers, and backup timers). As the spacecraft experienced the gravity of Mars the solutions began to converge and indicated that a 2.3- $\sigma$  execution error had in fact been introduced at TCM-6. This led to a westward ground change as indicated by the ‘OD133’ label in Figure 9. The final Navigation performance is 7 km to the south and west, as measured between the TCM-6 target and the ‘od133’ solution. The atmospheric dispersions and AEDL performance cause a movement of 13 km to the north and west, with a final distance of 22 km to the west of the E9 target.



**Figure 9. Post-Landing Reconstructions**

## CONCLUSION

The successful InSight landing would not have been possible without the techniques developed by the Navigation team. Combining the Thruster Calibration results with the ongoing small forces analysis was critical to the accurate prediction and characterization of the trajectory. A concerted effort to reconstruct TCM-5 made it possible to reduce risk on the mission by being prepared to execute the final TCM and an eventual ground error of only 9 km.

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